SCIENTIFIC, TECHNICAL, AND MANAGEMENT SECTION

Background

Extended Ionosphere

30 years of theory, beginning with Banks and Holzer [1968]; and observations, beginning with Shelley et al. [1972], have led to the recognition that the ionosphere is an extended plasma region that dominates not only the plasmasphere, but also the hot near-Earth plasma sheet and ring current regions, especially during times of geomagnetic disturbances [Moore and Delcourt, 1995 and references therein]. Traditionally, magnetosphere-ionosphere coupling has been modeled by taking the entire ionosphere as a thin layer described by its height-integrated characteristics. However, more recently [e.g. Winglee, 1998], it has become clear that the presence of the ionosphere throughout much of the magnetosphere mass loads the system and may actually enable the creation of the ring current, the principal manifestation of geomagnetic storms [Moore et al., 2001].

Current global simulations that describe the ionosphere as an extended region within the magnetosphere impose boundary plasma densities rather than fluxes [e.g. Winglee 1998]. Then all ionospheric outflows are driven by pressure distributions inside the simulation space rather than by ionospheric processes. Such models do a good job on the polar wind light ion outflows but do not yet realistically incorporate the low latitude *photothermal* plasmasphere, or the *induced* heavy ion outflows driven by structured sources of energy in the auroral zone. Low latitude outflows that fill the plasmasphere are eventually freed up to circulate through the entire magnetosphere during geomagnetically active periods as drainage plumes, as has been amply demonstrated in recent studies [Goldstein et al., 2003; Su et al., 2001; Foster et al., 2002; Chandler et al., 2003]. The auroral induced sources are strongly influenced by both electromagnetic (Poynting) and kinetic energy fluxes [Strangeway et al., 2000; Strangeway et al,. 2002] imposed by structured magnetospheric convection and precipitation.

In discussions at the Geospace Environment Modeling (GEM) workshops of the past few years, modelers have expressed the clear preference that empirical models of induced ionospheric outflows should be expressed in terms of the magnetospheric conditions imposed upon the ionosphere from the global simulation results, much as currents are now impressed upon the conductivity of the height integrated ionosphere. That is, induced outflows should be expressed in terms of the energy fluxes deposited in the ionosphere by magnetospheric processes. In this way, ionospheric outflows will be realistically responsive to such processes, participating in the global system dynamics as a feedback process that supplies additional plasma mass flux to the magnetosphere in response to its energy dissipation in the ionosphere. A conceptual framework for this was developed by Strangeway et al., [2002], and is illustrated in **Figure 1**. We are now in a position to include both photothermal and induced outflows in global simulation models, and need only translate empirical relationships into suitable code modules for their implementation within a suitable (multifluid) simulation code.

While the ionosphere is known to be important in the dynamics of our current magnetosphere, especially during active times, it will become much more important [Vasyliunas, 2003 during periods of reduced dipole moment such as that which will prevail during the

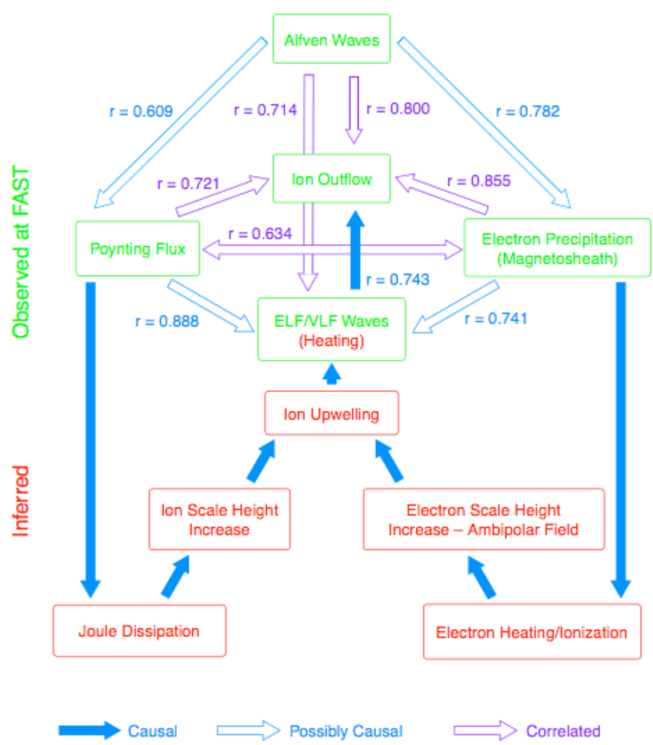


Figure 1. A conceptual framework for energy flow and resultant ionospheric outflow from below the exobase, after Strangeway [2002]. Low altitude joule heating of ions and precipitation heating of electrons are assumed to raise scale heights, while ELF/VLF ion heating at higher altitudes imparts escape energy to the outflows.

geomagnetic reversal that we have for some centuries been entering [Cox, 1969]. Since biblical times, the dipole moment is has halved, and the rate of change is accelerating in recent decades [Merrill, 1999], such that extrapolation suggests a reversal minimum in a few 100 years. With the proposed attention to realistic modeling of the extended ionosphere, our tools will have reached a state of readiness to be tested on a wider range of parameters with greater ionospheric importance and impact. We propose here to investigate the behavior of the geomagnetosphere during a magnetic field reversal, for which this capability will be enabling.

Siscoe et al. [1976] conjectured that only the dipole moment is reduced during a reversal, concluding that the higher multipoles would be sufficient to prevent the Earth from reaching a Venus like state with direct interaction of the solar wind and ionosphere. Siscoe and coworkers [1976; 1979, 1980] also considered the auroral zone shapes that would result. Neverthless, it is clear that the magnetosphere will go through stages in which it becomes more similar to the magnetospheres of other terrestrial planets, which in general have smaller dipole moments than that of the Earth, in absolute or relative terms. If the dipole moment drops sufficiently below its present value, the magnetosphere will more closely resemble that of Mercury, where the upstream standoff distance is < 1.5 planetary radii. If it drops even lower than that, it will more closely resemble the Martian interaction with the solar wind, with higher multipole moments imparting a local structure not unlike the local crustal magnetization features of Mars [Curtis and Ness, 1988; Acuna et al., 2001]. If the higher multipole moments drop as well, Earth will resemble Venus' solar wind interaction. Thus, a consideration of space climate during a geomagnetic reversal should encapsulate the entire study of comparative magnetospheres for the terrestrial planets. Moreover, during a reversal period with appreciable remanent dipole moment, as the orientation rotates through 90° relative to the spin axis, a magnetosphere similar to that once expected for Uranus (before the Voyager encounter) [Selesnick and Richardson, 1986, Selesnick, 1988] will briefly exist.

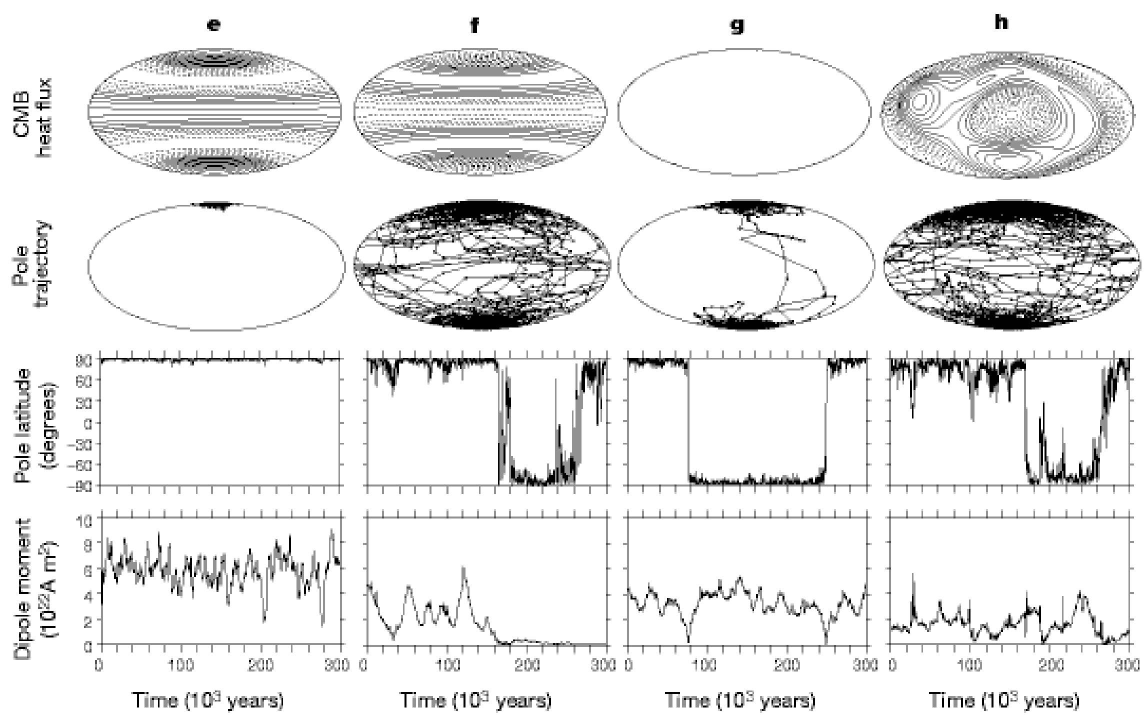
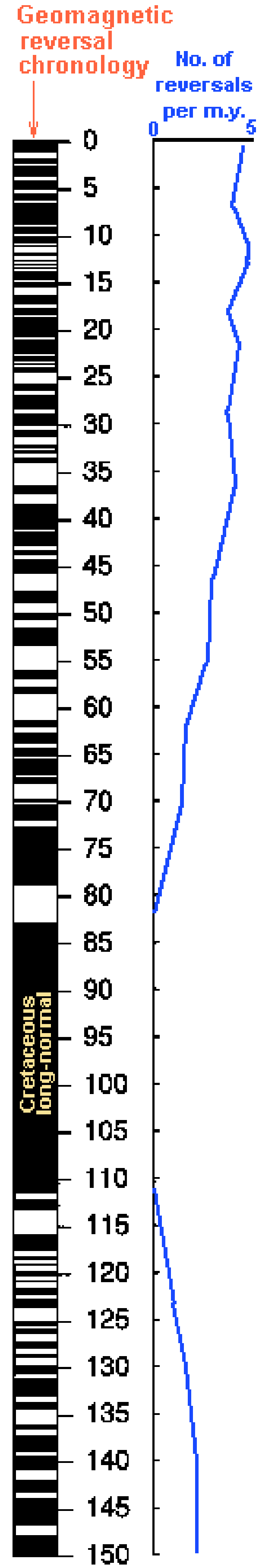


Figure 2. Dynamo simulations, after Glatzmaier et al. [1999]. Cases correspond to varying imposed patterns of radial heat flux at the core-mantle boundary. Top row: the pattern of heat flux in projection over the boundary with geographic north at the top-center and south pole at bottom-center. Solid contours represent heat flux enhancements while broken contours represent heat flux depressions relative to mean. Case e has bands of enhancement with a polar peak, while case f is the inverse. Case g is the isotropic case, while case h represents a more realistic case. Second row: trajectory of the south pole of the dipole moment spanning the times indicated in the plots below. Third row: plots of the polar latitude of the dipole moment versus time. Fourth row: plots of the magnitude of the dipole moment versus time. All simulations began long before the zero times plotted.



Geodynamo

The geomagnetic field is known to exhibit quasiperiodic reversals on a time scale of a few hundred thousand years, involving distinct flips of polarity that occur at average frequency of about 5 per My, with longer term modulations of frequency, as shown in the sidebar chart [S Earle, http://www.mala.bc.ca/~earles/reversals.htm]. Extrapolation of the current dipole evolution may not be accurate, but the geologic record shows that future reversals are a certainty.

But do we know the character of reversal fields well enough to model the solar wind interaction throughout the process? The answer is an unqualified "yes". During the past decade, the theory of the geodynamo has been substantially developed through 3D simulations that run for a few 100 kyrs, with a resolution of ~15 days [Glatzmaier and Roberts, 1995]. These simulations exhibit realistic polarity reversals within (barely) practical run times. The modeled dynamo is thermally driven, and responds dramatically to varying assumptions concerning the distribution of heat flow from the Earth's core to space [Glatzmaier et al., 1999; Roberts and Glatzmaier, 2000]. In the realistic cases, a reversal involves a reduction of the dipole moment of the Earth, and to a varying degree, a turning of the residual dipole moment from one spin pole to the other, followed by a restoration of the original dipole moment in the opposite direction. The minimum dipole moment during a reversal is typically <10% of the quiescent dipole moment, but it can be larger or smaller depending on a number of factors. **Figure 2** illustrates a range of possibilities. Most cases exhibit behaviors that can be described as impulsive polarity flips of the geomagnetic field. In many cases the dipole moment dips substantially during the rotation of the dipole orientation; in other cases it does not dip as much.

Recent simulation work has thus created a quantitative basis for investigating the solar wind interaction during a geomagnetic reversal. Simulation results can be used as a determination of the likely internal field of the Earth at any stage of the reversal process. The full coefficients for these internal fields are available on a 15 day resolution basis for any of the events shown in Figure 2, and for many other cases as well. G Glatzmaier will collaborate with us in this study, supporting us with a supply of geomagnetic field descriptions from his simulation work, exemplary of the generic states attained by the field during the process of reversals.

It is relatively straightforward to insert an arbitrary internal field into a magnetospheric field model or a global simulation of the solar wind interaction. Doing so may drastically alter many of the conditions being modeled and may require adjustments in the modeling framework. Nevertheless, it should be clear from the discussion above that the tools exist with which to begin the task of predicting the kinds of magnetospheres we will have during the process of a geomagnetic reversal, which may be underway at the present time. This is a proposal to do just that, to first establish a realistic extended ionosphere within a simulation of the current magnetosphere; then to simulate the future magnetosphere at representative stages of a field reversal; then to validate our results by comparison with observations of the magnetospheres of the terrestrial planets Mercury, Mars, and Venus.

In the following sections of this proposal, we summarize recent progress made under our prior support, forumulate a specific set of science objectives for the present proposal, summarize our approach and the specific studies we are planning. Finally, we summarize and point out the relevance of our proposed work to the Sun-Earth Connection Geospace Sciences program.

Recent Progress

Mercury Ion Dynamics

In recognition of Messenger, a NASA Discovery mission being developed for exploration of Mercury, and Bepi Colombo, a Mercury mission being planned by ESA, we have begun to study the character of the Hermean magnetosphere and hermeosphere.

The latter is a region dominated by Mercury’s exosphere, containing exotic materials such as sodium, sputtered from the planetary surface.

One study [Delcourt et al., 2002] considered ion dynamics in the Hermean magnetosphere, and evaluated the effects of smaller radius field curvatures associated with the smaller overall size of this magnetosphere. The simulations demonstrate that centrifugal effects play a substantially more prominent role in the net particle acceleration than in the terrestrial magnetosphere. It is found that, at Mercury, the acceleration due to ExB drift path curvature may greatly exceed that due to magnetic field line curvature even for moderate convection rates, a situation which contrasts with that prevailing at Earth. At Mercury, ExB related centrifugal effects can yield heavy ion energization of hundreds of eV within minutes, which is at least two orders of magnitude above that achieved in the Earth’s magnetosphere.

In the second study [Delcourt et al., 2003], we explored the behavior of Na^+ ions of planetary origin at Mercury, which exhibits several features of interest linked to the small spatial scales of the Hermean magnetosphere. First, because of the pronounced curvature of the ExB drift paths, significant centrifugal acceleration occurs during transport from high to low latitudes so that the magnetospheric lobe content is found to be significantly more energetic (several hundreds of eV) at Mercury than at Earth. In the innermost region (typically, within 2 R_M radial distance), this non-adiabatic behavior is characterized by prominent pitch angle scattering (□ ~ 1) which hampers stable trapping at low latitudes. At larger distances, quasi-adiabatic (Speiser-type) behavior occurs together with several keV ion energization. The net result of this non-adiabatic circulation is a quite substantial filling of the inner tail and a thin sheet of energetic Na^+ ions at larger distances, as shown in **Figure 3**. Because of a less dense exosphere, the density from planetary ions is found to be smaller at aphelion. Also, the non-adiabatic motion of ions in the magnetotail is responsible for a narrow band of energetic precipitation in each hemisphere at the planet’s surface. These bands, which extend over several degrees in latitude and a wide range of longitude, should lead to additional sputtering of planetary material. The poleward boundary of these bands corresponds to the limit of slow gyromotion in the magnetotail and thus depends on ion species. This latter gyroradius filter effect forms a specific feature of the large-scale magnetic mass spectrometer at Mercury.

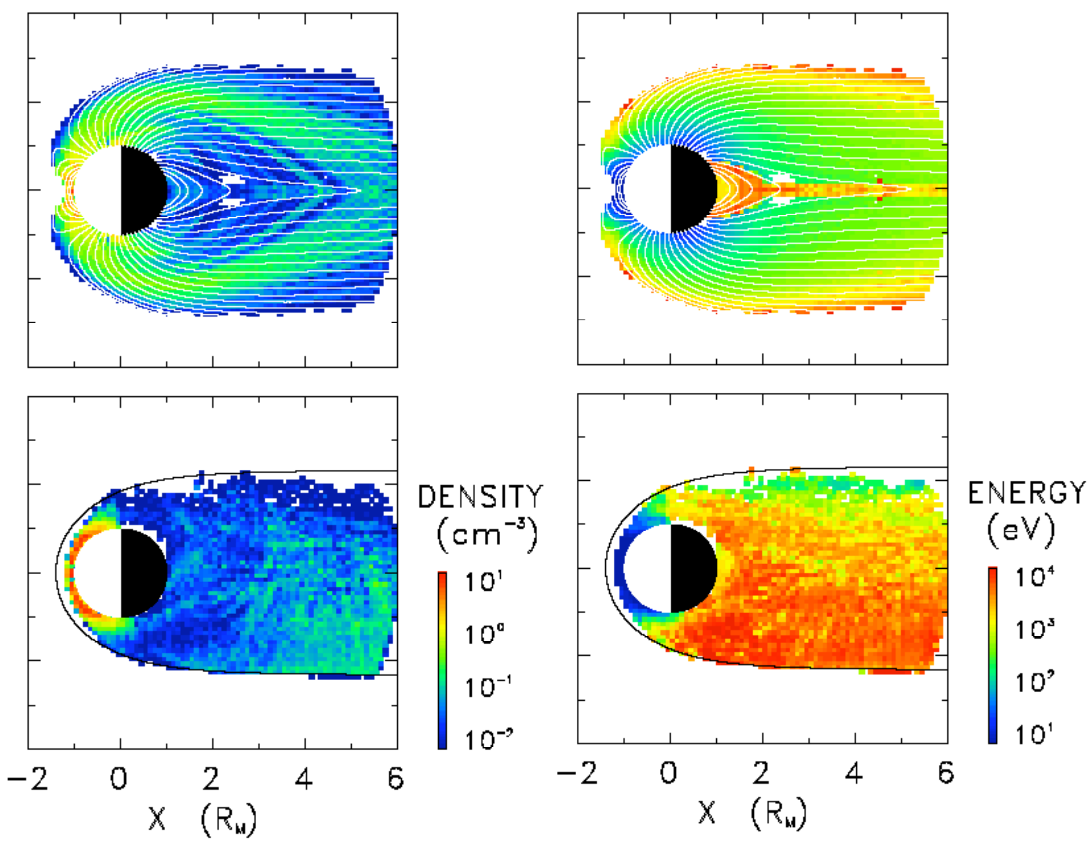


Figure 3. Color-coded density and mean energy of Na+ ions in the Mercurial magnetosphere as derived from 3D particle simulations. After Delcourt et al. [2003].

Venus/Mars Solar Wind Interaction

Recognizing that Venus and Mars are both candidates for further exploration, we have also begun to study the Venusian solar wind interaction. In this case, virtually no intrinsic field or extended magnetosphere exists, so that the solar wind is directly incident upon the upper atmosphere and ionosphere. Consequently, one expects a relatively direct aeronomic interaction in which both charge exchange and scattering collisions will be frequent with substantial emission of fast neutral atoms and collisional dissipation resulting in sputtering escape of upper atmospheric gases. We used the multifluid magetodynamic simulation results of Tanaka and Murawski [1997] to provide a description of the plasma and fields, along with the exospheric model of Keating et al. [1985]. With the goal of estimating neutral atom emission, we folded together the plasma and gas models to generate line of sight integral atom fluxes, with results illustrated in **Figure 4.** The simulations show the following: Neutral atom imaging is a useful tool for studying the solar wind interaction with the terrestrial planetary magnetospheres over the range of magnetization from Earth to Venus. Significant low-energy (0 – 10 keV) neutral atom emissions are expected fromVenus. Venus magnetosheath emissions have similar features and comparable intensity as those from the Earth during extreme solar wind condition. Low-energy neutral O images from Venus can be used to probe the location and dynamics of the ionopause.

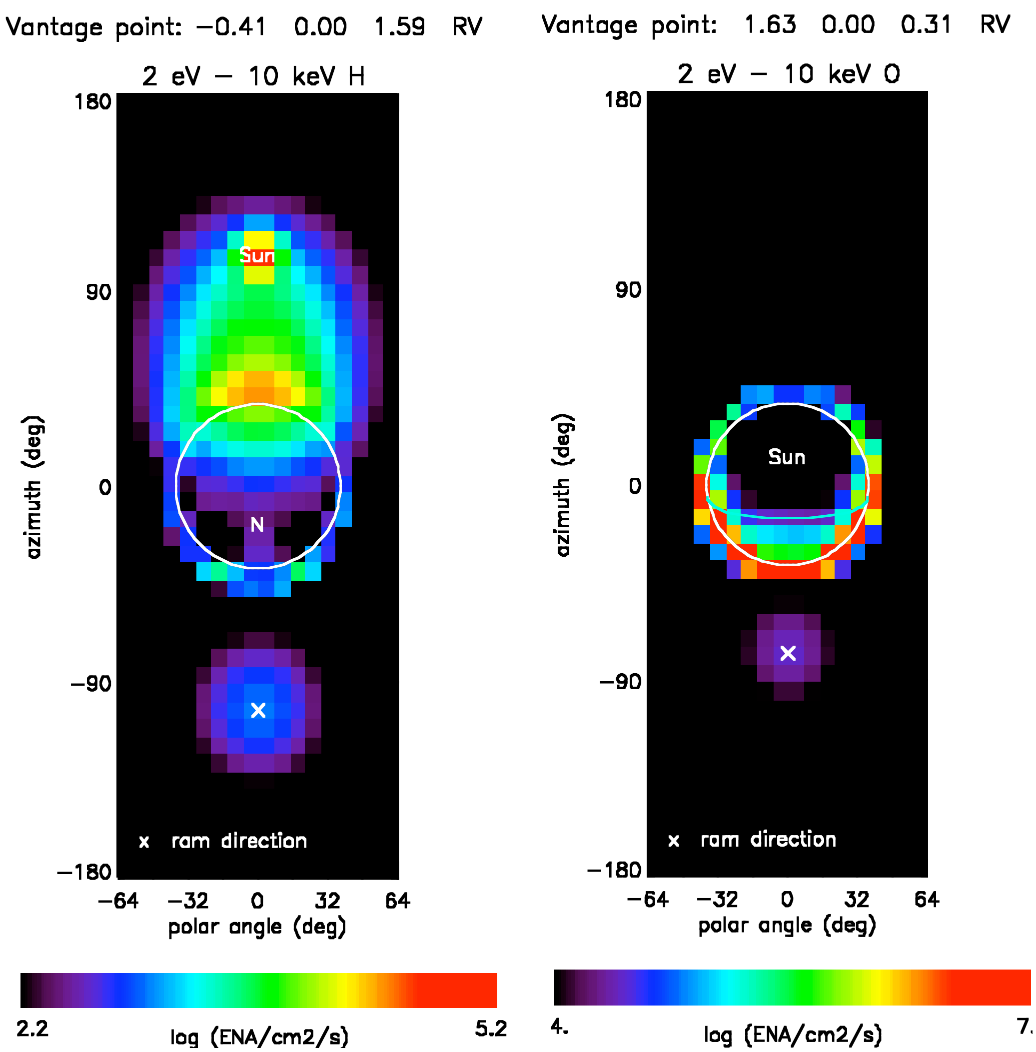


Figure 4. Simulated Venus H (left) and O (right) ENA images for the energy range from 2 eV to a few keV. The white circle is the rim of the planet and the blue circle is the equator. [Fok et al., 2003].

Dayside Reconnection

Motivated by Polar observations [Chandler et al., 1999] we explored dayside reconnection theoretically, with the goal of examining whether high and low latitude reconnection might occur simultaneously [Moore et al., 2002]. The result is that we find it quite plausible, and indeed we find it to be an essential property of the dayside reconnection X-line for typical interplanetary magnetic field clock angles near 90˚ or more northerly than that. We revisited arguments in the literature concerning “component” reconnection and “anti-parallel” reconnection, and developed a method for integrating the shape of the X-line across the dayside magnetopause, thus unifying both types of reconnection., since in general the X line extends well away from its intersection points with the locus of antiparallel fields.

Opinion has recently favored the limitation of reconnection primarily to regions where the reconnecting fields are nearly anti-parallel, as shown in **Figure 5**, left panel. Where the fields do no approach anti-parallel, only a component of the fields is available for so-called “component” reconnection, and the remainder of the fields is directed along the “X-line”, in the form of a so-called “guide field”. However, there is a problem with anti-parallel reconnection, in that the direction of the X-line tends to run perpendicular to the local magnetic fields whereas the region of anti-parallel fields tends to run parallel to the local magnetic fields. As a result, there can be at most a very short X-line within a given region of anti-parallel fields. Multiple short X-lines could be invoked, but it is difficult to see how the aggregate of a series of short parallel X-lines lying across an antiparallel field region could add up to a significant transpolar potential in the global picture.

As an alternative, we explored the hypothesis that an X-line forms at the region with the largest reconnecting field components (presumably at or near a region of antiparallel fields) but then spreads away from that region along an X-line that is integrated from point to point along the magnetopause like a vector streamline. The result is shown in **Figure 5**, right panel, where the X-line has been mapped across the magnetopause for several different clock angles. Boundary layer flows were calculated according to the procedure of Cowley and Owen [1989].

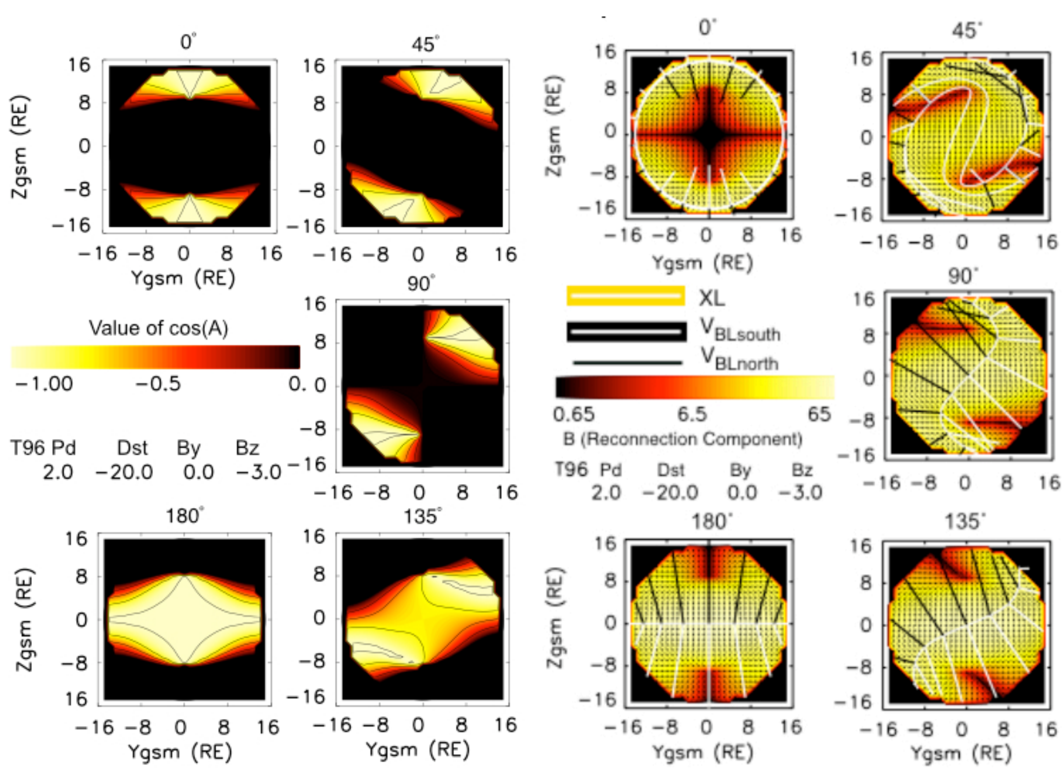


Figure 5. Comparison of antiparallel reconnection sites (left) with the dayside reconnection X-line (right) calculated by integrating the component reconnection X- line (white curve) away from regions of maximal reconnecting component, for selected clock angles. Vectors emanating from the X-line indicate boundary layer flow. [Moore et al., 2002].

MFMD Simulation of a 90˚ Tilt Magnetosphere

We also initiated our previously proposed collaboration with R. M. Winglee of U. Washington, who has developed an innovative multifluid magntodynamic (MFMD) global simulation code that tracks separately solar wind ions, ionospheric ions of multiple species, and electrons. We are running this code at GSFC and have assigned staff to analyze the code and refine it where possible, with the goal of parallelization for accelerated performance on massively parallel processor facilities. To gain experience with the code our initial efforts have focused on preliminary investigations to the work proposed here. To simulate a case of interest for geomagnetic reversals, we reduced the terrestrial dipole moment to one half its current value, and tilted it so that the north magnetic pole points toward the sun. The results are fascinating and familiar in some ways though unfamiliar in others. **Figure 6** illustrates some salient characteristics of the resultant magnetosphere, in a case where it is oriented“pole-on” to the solar wind direction.

As shown in Figure 6, there is only a single cusp, and only a single magnetotail lobe. Dayside reconnection links interplanetary field lines into the sunward facing pole, and extends azimuthally some fraction of the way around the sun-Earth line, encircling the dayside cusp and centered on the azimuth where the IMF is anti-parallel with the local geomagnetic field. A more or less semi-cylindrical plasma sheet forms, wrapped around the single tail lobe, and offset toward the sun-Earth line azimuth that is opposite to that of the peak (anti-parallel) dayside reconnection. The single lobe contains outflows of cold ionospheric plasma, while the plasma sheet contains Earthward flows of hot ionospheric and solar plasma. The solar hydrogen density minimizes in the plasma sheet, while the ionospheric hydrogen density maximizes there.

Our initial results compare well with earlier work on high tilt (Uranus) magnetospheres by Wu, [1984], and Walker et al. [1989]. Those earlier efforts had zero IMF magnitude, resulting in near-perfect symmetry, whereas ours is highly asymmetric owing to reconnection with the IMF. In our case, the dipole also rotates diurnally, such that the pole will in 6 hours be pointing duskward, returning the global magnetosphere to a more normal two-cusp, two-lobe configuration, albeit one that still has its magnetic poles at the equator. Then the pole will rotate to the tail, through dawn, and back to the orientation shown here. It should be apparent at this point that a magnetosphere like this one will generate an auroral light show like none in recorded history.

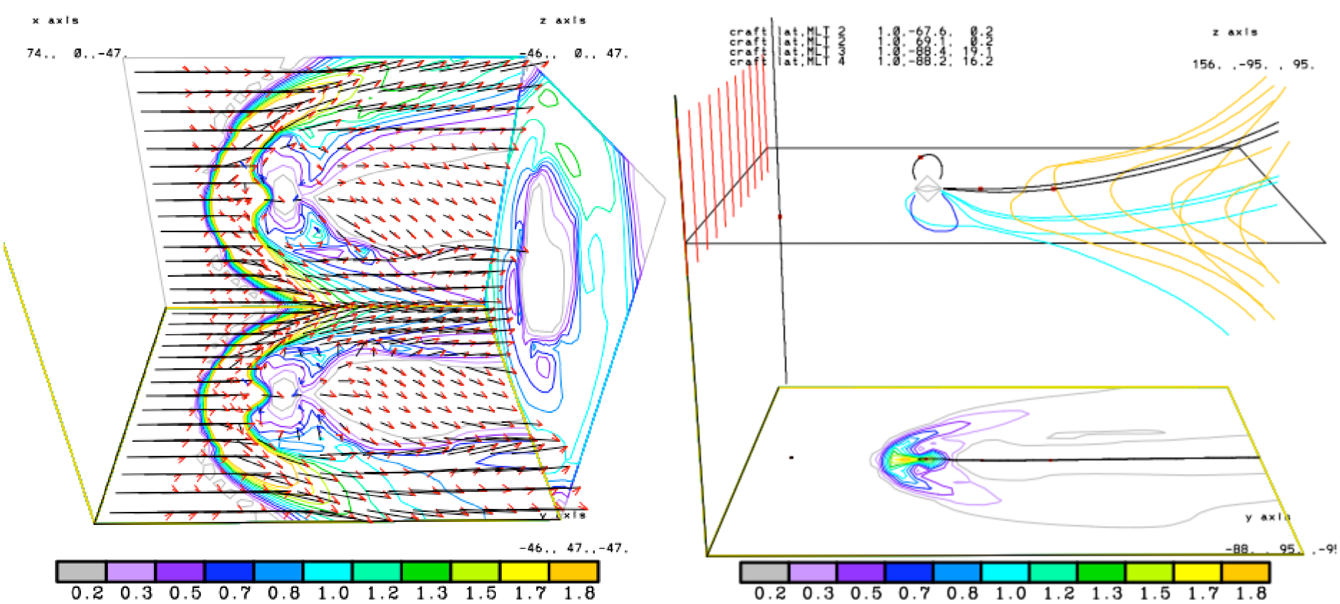


Figure 6. Left – X-Y and X-Z slices with color contoured total pressure and vector flow. A Y-Z slice at right is offset to X=-12.5. Reconnection flows are visible in the upper left magnetopause region. Right – Similar X-Y slice but zoomed out, with color contoured solar wind pressure in the ecliptic plane and representative magnetic field lines in the upper box, showing offset plasma sheet formation.

Science Objectives

The following objectives are set for their significance to the space physics community at large and because they are addressable using the tools we have developed and extended in our previous studies:

1. Develop a global model of the current magnetosphere with a realistic extended ionosphere including photothermal and induced outflows, and use it to investigate common space weather events.
2. Consider and investigate the long term behavior of the magnetosphere using the global simulation for representative cases ranging through all phases of a simulated geomagnetic reversal.
3. Investigate the kinetic behavior of particles in the simulated present and future magnetospheres using kinetic simulations in global simulation fields, over the relevant energy range.
4. At phases of geomagnetic reversal for which the Earth's magnetosphere most closely resembles those of the other terrestrial planets, compare results with relevant observations and tailored simulations.

The Extended Ionosphere

An important aspect of the proposed work is the specification of the ionospheric boundary conditions, both as lower boundary conditions for the multi-fluid code, and as source distributions for phase space density weighting of single particle trajectories. To do this, we will use outflow observations and modeling results from the literature, especially results that have been obtained from the FAST mission by R J Strangeway and coworkers [Strangeway et al., 2000; 2003], as well as similar work being done on the Polar spacecraft data set [Zheng et al., 2003]. Representative results illustrating the two main parameters from the latter study are illustrated in **Figure 7,** Here the the DC Poynting flux and the precipitating electron density were confirmed as the most powerful drivers of total outflow flux.

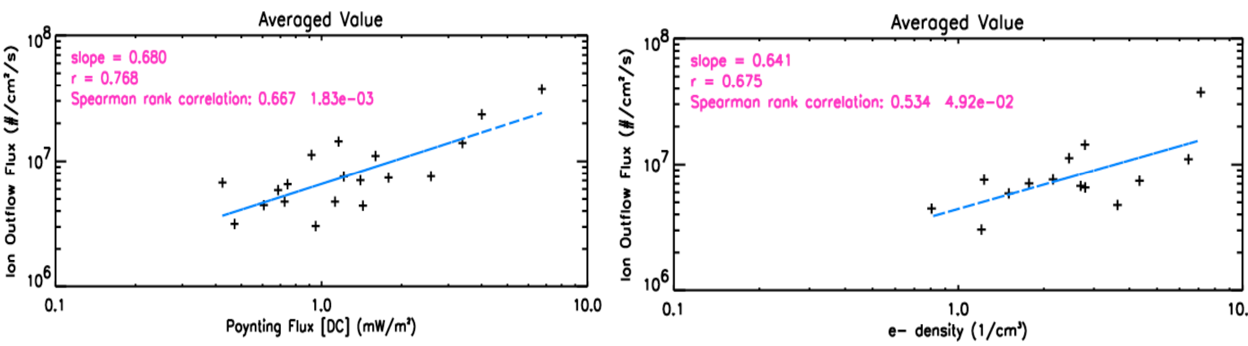


Figure 7. Results from a Polar Mission study of the local influences on ionospheric outflow using perigee pass data (~5000 km altitude) from 19 events. The two parameters that emerged as the strongest determinants of outflow flux were the DC Poynting Flux and the precipitating electron density (strongly weighting low enery electrons around 3-100 eV), in agreement with FAST results reported by Strangeway et al. [2002].

Following suggestions made during discussions at the annual NSF-GEM workshops, we will develop a boundary module for outflow response to local conditions to be supplied to the multi-fluid code, to assure a degree of self-consistency and responsiveness to system feedback. We will scale the heavy ion outflow with the important energy fluxes into the ionosphere implied by multi-fluid conditions of density, temperature, and electric field, representing both the electromagnetic (Poynting) flux and the particle precipitation energy flux, or a suitable proxy for each. This relationship will be presumed to depend only on solar conditions and to be independent of all other parameters.

The induced heavy ion outflow flux will be superposed upon a pervasive photothermal light ion outflow flux, assumed to fill the plasmasphere and exist everywhere outside of it. The magnitude of this outflow flux will depend only on solar zenith angle [Su et al., 1998] and high altitude pressure buildup. A steady state model will therefore create a plasmasphere as an intrinsic feature of the model. When simulating dynamic storm events, the resultant plasmasphere will respond self-consistently to the global convection pattern, producing the observed drainage plumes that supply light ion plasma to the dayside magnetopause region [Chandler et al., 2003].

Magnetospheric Impact

Winglee [1998, 2000] has shown that the clearest impact of ionospheric plasma on the magnetosphere is mass loading of convection, with substantial reduction of the transpolar potential reaching the ionosphere. This corresponds to the absorption of energy by acceleration and heating of extended ionospheric plasma in the lobes, plasma sheet, and ring current regions. Essentially, energy dissipation ($\mathbf{J}\bullet\mathbf{E} > 0$) becomes much more widely distributed rather than being limited to the ionosphere proper. With our improved, realistic description of the extended ionosphere, we will revisit the impact of ionospheric plasmas and their energy absorbing capabilities, looking for new modes of behavior as well as other, more subtle and-or quantitative changes in magnetospheric dynamics stemming from the presence of an extended ionosphere.

Recent observations and modeling results have made it clear that, even during relatively quiet times (except for northward IMF periods), the photothermal outflows of lobal winds supply the plasma sheet with a substantial amount of plasma, while at the same time, evidence has been found that solar wind plasmas present in the more distant tail, beyond about 30 RE, have very little opportunity to be transported back to the near-Earth region. Our suspicion is that a serious modeling effort to include a realistic extended ionosphere, such as we propose, will suggest that the principal energy flow in the magnetosphere is from the solar wind to the extended ionosphere, and thence into the ionosphere proper, with relatively little re-energization of solar wind plasmas that have been slowed down by their interaction with the dayside or flank magnetopause regions. If this is borne out, it will force a substantial revision of the current paradigms of magnetospheric physics.

The impact of the extended ionosphere will only increase as the Earth progresses further into the current geomagnetic field reversal. To study this quantitatively, we will be rebuilding our simulations with selected typical snapshots of the geomagnetic field from the simulations of Glatzmaier and Roberts [1995]. For example, in case g of Figure 2, the magnetic field magnitude is substantially depressed from our present field, and is dominated by the higher multipoles, as illustrated in **Figure 8.**

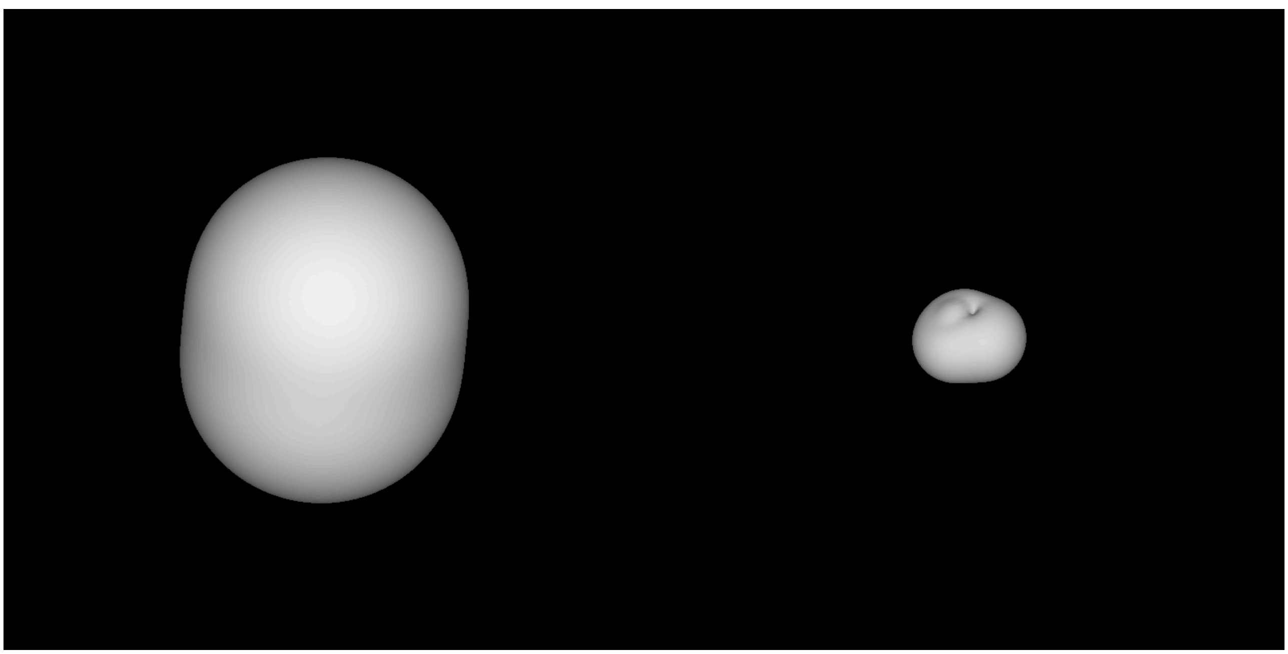


Figure 8. A comparison of the size of the 30 nT isosurface for the IGRF (2002 geomagnetic field; mainly dipolar on this scale) and for the Glatzmaier et al. [1999] field during a simulated geomagnetic minimum during a reversal event (case g of Figure 2). It is irregular, with a prominent lumps and dimples.

It is clear from Figure 8 that Earth will have a much smaller magnetosphere than at present, and that it will have many unfamiliar features, including weak field regions such as the dimple there. It is clear that the magnetosphere will be substantially less effective as a shield from external radiation, and that it's patterns of convection, auroral formation, and energetic particle acceleration will be substantially different as well. All of these things can be calculated and evaluated using the tools we propose to develop. A major determinant of the behaviors of such a magnetosphere is the occurrence of reconnection that links it with the external solar wind medium.

Reconnection Impact

Figure 9 is a sketch of the qualitative nature of a high-tilt magnetosphere as it would be realized if a geomagnetic field reversal passes through a state with the dipole axis normal to the spin axis. The view is in the ecliptic plane of the average Parker spiral interplanetary field. The planetary rotation phase is captured here at the moment when the dipole axis points sunward, a real simulation for which was described in the previous section (albeit with opposite pole orientation).

It is immediately apparent that the concept of magnetic local time in such a system will lose its usual meaning. The magnetic tilt of such a magnetosphere will undergo a diurnal cycle over the full range of possible values. The aurora will become a mid to low (geographic) latitude phenomenon, favoring certain geographic longitudes, depending on the reduction of the dipole moment. Moreover, the aurora will also undergo a diurnal cycle in which it twice a day assumes forms that are familiar from our present magnetosphere (apart from their geographic distribution), with both dusk and dawn ovals exhibiting dayside and nightside parts that are distinct from each other. During the intervening UT quadrants like the one shown in Figure 9, when the ovals are centered near noon and midnght, the entire dayside auroral zone should more closely resemble our present dayside auroras, while the entire nightside auroral zone should more closely resemble our present day nightside auroras.

Using field configurations as given by geodynamo simulations, we will build a corresponding series of global magnetospheric simulations that support determination of a quantitative form of the magnetosphere, including its circulation and energy flow patterns.

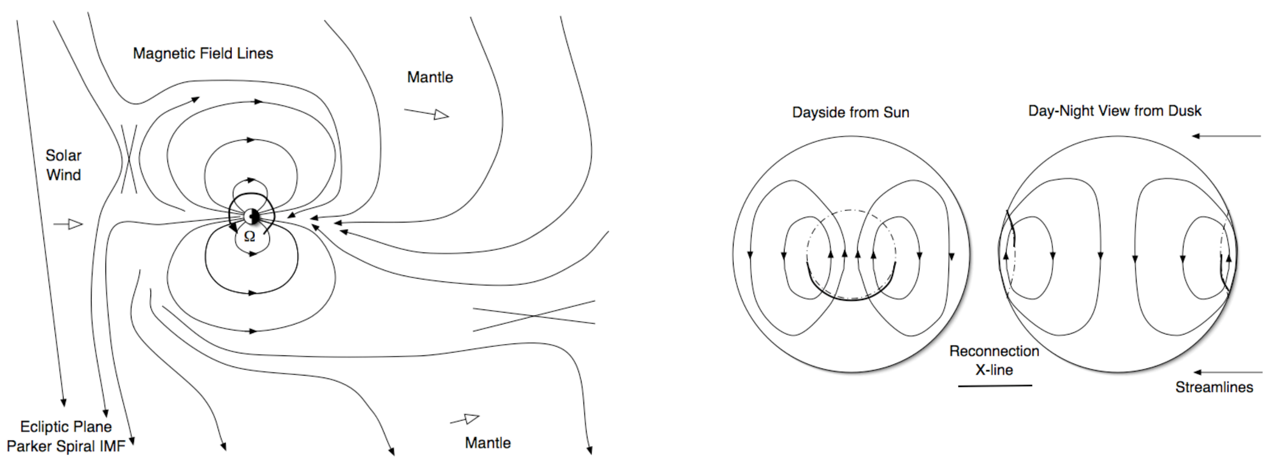


Figure 9. A sketch showing (left) the qualitative nature of a high-tilt magnetosphere with an IMF, as the ecliptic plane projection of magnetic field lines and flows. The axis of rotation remains near normal to this plane. The right panel shows the expected ionospheric convection pattern from two perspectives as indicated.

The very high tilt (90˚) cases will provide an invaluable exploration of the effects of IMF orientation over a wider range than we have previously seen or simulated, testing our ideas concerning the distribution and operation of dayside reconnection. The sketch in Figure 9 has been drawn based upon our recent results in this area [Moore et al., 2002]. In three dimensions, we expect that the reconnection X-line will form at the dipolar magnetic longitude where the IMF and dipole field are anti-parallel, and radiate away from that site along a curve that will circumnavigate in some fashion the single sunward cusp, the reconnection rate having a significant peak where the fields are anti-parallel, and lower rates elsewhere along the X-line. This reconnection will drive a convective flow across the dayside polar cap from the dipole longitude of anti-parallel fields to the dipole longitude of parallel fields. Our first simulation efforts, as reported above, are qualitatively consistent with this description, though details remain to be studied. On the nightside a neutral sheet will be created as roughly a half cylinder shape, dividing sunward from tailward directed field, and reconnecting in such a way as to return flux to the inner part of the magnetosphere. As strange as this magnetosphere appears, it still will have some familiar features and functions.

The past two years have brought a revolution in our appreciation for the reality of storm-time plasmaspheric erosion [Sandel et al. 2001; Su et al., 2001; Foster et al., 2002] and its impacts on the dayside magnetopause region, as well as the other regions downstream in magnetospheric circulation. Supporting these remote sensing observations are an increasing number of reports [Sauvaud et al., 2001; Chandler and Moore, 2003; Chen and Moore, 2003] showing that relatively cold ionospheric plasma is a substantial component of the outer dayside magnetosphere, just inside the magnetopause.

The implications of these newly discovered facts include a potential impact on dayside reconnection, since the amount of ionospheric plasma varies broadly from less than 0.1 cm-3 to over 50 cm-3 at the subsolar magnetopause, depending on the history of convection. This implies a similar variation of the Alfvén speed and the limiting rate of reconnection in that region. Thus, we have the prospect that magnetospheric circulation driven by dayside reconnection should be self-limiting when it draws a substantial part of the plasmasphere out to the subsolar region, depressing the local Alfvén speed. With a much smaller, possibly complex magnetosphere during a reversal, extended ionospheric plasma transport will be increasingly prominent in the magnetopause region.

Plasma Sheet and Energetic Particles

We will investigate the non-adiabatic kinetics that occur in the field reversal magnetosphere, including particle acceleration to plasma sheet, ring current, and radiation belt energies by processes known to be important in the present day magnetosphere. The pervasive features of inner magnetospheric circulation will include the induced oxygen-enhanced cleft plasma fountain and high latitude photothermal flows (referred to here as "lobal winds"), hot outflows from the auroral zones ("auroral winds"), bidirectional streaming distributions, and resultant hot isotropic distributions of plasma.

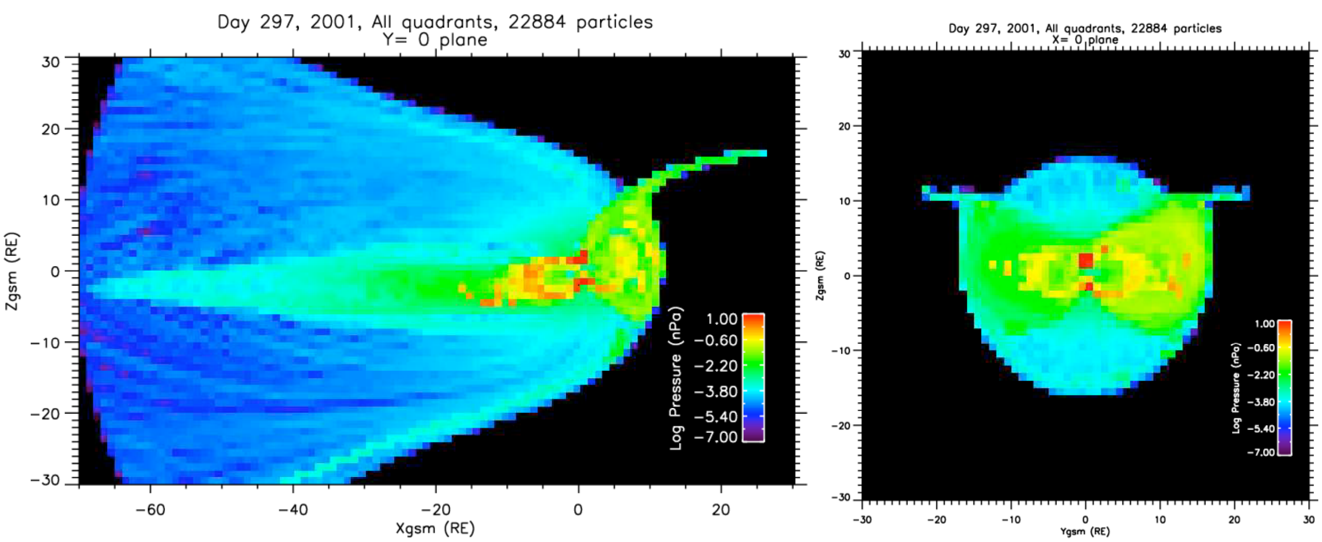


Figure 10. A kinetic simulation of the magnetosphere based on polar wind H^+ trajectories in empirical model fields (Tsyganenko 89, level 2, modified Stern-Volland with appropriate transpolar potential ~50kV), using the full motion code of Delcourt. Based on 20000 particles emitted from all local times and latitudes above 55° invariant, velocity space distributions have been integrated in 1 RE cubes to derive the plasma pressure.

The study will begin with electromagnetic fields within which the test particles will travel, determined from the multifluid magnetodynamic simulations. Next, particle weightings and trajectory initial conditions will be set based on the global simulated lobal and auroral wind properties and spatial distributions. A large number of particle trajectories will be launched with random spacing across the range of parameters indicated by the observations, in both velocity space and physical space. A prototypical example of the resultant trajectory database is shown in **Figure 10**, where we have used empirical photothermal light ion outflow results and empirical field models to exercise the trajectory simulation and database codes. We have populated space with over 20000 particles here, so that their distribution can be examined within relevant parcels to investigate the opening hypotheses. It can be seen in Figure 10 that a clear plasma sheet is formed as the particles are compressed nonadiabatically in preparation for Earthward transport, and accelerated substantially. The eventual pressures in the inner magnetosphere approach 1 nPa, comparable with moderate ring current pressures. Other plots (not shown) of parallel flows demonstrate the formation of a layered plasma sheet boundary region of nested tailward and Earthward flows. Perpendicular flows are largely random but a clear westward drift emerges in the inner plasma sheet and the entire ring current region torus.

This preliminary effort must be complemented by similar studies of entering solar wind particles, as well as induced ionospheric outflows of heavy ions. We will investigate these energetic particle populations in the current and future magnetosphere in these and other ways using the tools described below, following up on earlier suggestions by Ultré-Guérard and Achache [1995], and Willis et al., 2000.

Proposed Approach

We propose a coupled test particle and kinetic 3D magnetospheric simulation effort, using global multi-fluid magnetodynamic MFMD simulations to create the field and plasma source context within which we will study localized departures from adiabaticity.

Multi-fluid MagnetoDynamic and MHD Models

We have successfully developed a kinetic particle interface with the Lyon Fedder Mobarry single fluid MHD code, and thereby demonstrated the feasibility of this work with a single fluid model. It will be relatively straightforward to carry this over to a multi-fluid code having similar computation grid.

The multi-fluid magnetodynamic code we will use was developed and reported by R. M. Winglee [1998, 2000], to which the reviewer is referred for substantial details, which include a description of the partial inclusion of parallel pressure gradient and magnetic drift effects, albeit at the thermal speed only. This remains the only model of which we are aware that currently includes a separate fluid (or fluids) representing ionospheric outflows. However, this statement may no longer be valid by the time this work begins, as other simulation efforts are picking up on this practice. One of our top priorities will be to compare specific cases with and without substantial photothermal ionospheric outflows, and with and without substantial induced heavy ion outflows. This will substantiate the effects of an extended ionospheric fluid within the simulation space, which is also relevant to comparisons with other magnetospheres such as that of Mercury, where the ionospheric source is much less important dynamically, or Venus, where it is much more important.

Outer Magnetosphere Full Particle Model

Our test particle model has been described extensively elsewhere [e.g. Delcourt et al., 1993, and references therein]. Empirical 3D models of magnetospheric magnetic and electric fields have been used extensively as a basis. For each time step, the fields can be locally evaluated by tracing a triad of field lines to the ionosphere to map the electric field model to the particle position. This technique compensates with accuracy for what it gives up in computational efficiency, as demonstrated by our test of reversibility in connection with exploration of the plasma sheet source groove [Moore et al., 2000].
The software interfaces we have recently added now allow the use of any available model that returns the required fields from positional inputs, including the more advanced Tsyganenko [1995, 2001] models.

Ensembles of particles are initiated from appropriate source locations with characteristic initial conditions, and advanced in the model fields using the full equations of motion. We have the choice of whether to use empirical analytic fields expressed in the ionosphere or local specification of the electric field by a 3D simulation. An interpolation scheme is used to obtain the field at points within an global computational grid, with acceptable loss of accuracy, limiting to some degree the long-range accuracy of the trajectories.

We also propose to extend the use of this particle model to investigate the acceleration of electrons in the plasma sheet, looking for the effects that result in their relatively low temperature as compared with the co-located ions. This will require us to work with global simulation fields rather than empirical ionospheric convection patterns.

Inner Magnetosphere Kinetic Particle Model

The inner magnetosphere model we will use in this work is the Fok kinetic model that solves a Boltzmann initial/boundary value problem with specified electric and magnetic fields, including the effects of charge exchange losses, wave particle diffusion effects, and Coulomb drag on energetic particles interacting with hydrogen geocorona and the plasmasphere, respectively. Rather than tracking particles trajectories in detail, a bounce-averaged approach is taken. A full description of this ring current model is given in Fok et al. [1995, 1996, 2001a].

The Fok kinetic model has recently been combined with the Rice convection model (RCM) to provide self-consistent electrodynamic coupling with the ionosphere proper (Comprehensive RCM or CRCM). To couple with the Fok model, the RCM algorithm for calculating Birkeland current has been generalized to arbitrary pitch angle distribution [Fok et al., 2001b]. Given a specified ionospheric conductance and initial ring current distribution, the RCM component of the CRCM computes the ionospheric electric field and currents. The Fok model then advances the plasma distribution using the electric field computed by the RCM and at the same time calculates particle losses along drift paths. The updated distributions are then returned to the CRCM to complete the computation cycle. Input models required for running the CRCM include a magnetic field model, transpolar potential, an ionospheric conductance model, and the plasma sheet distribution function at the equator at the CRCM outer boundary.

Overall, the global fields and plasma inputs to the magnetotail will be produced using the Winglee MFMD, based on a physical-empirical model of ionospheric outflows and their response to fluid conditions at the inner boundary of the multi-fluid simulation. The plasma sheet effects on inflowing plasmas will be included using the Delcourt 3D particle motion code. The effects within the inner magnetosphere will be included using the CRCM, which includes ionospheric electrodynamics coupling. The combination of these models provides the best of all worlds by including self-consistent fields both globally and within the inner magnetosphere, while tracking important non-adiabatic effects where they are important.

Work Plan

Year 1

- Implement photothermal outflows and corotation to generate a simulated plasmashere and polar wind. Test the impact of these outflows on the present magnetosphere using reference events.
- Implement induced auroral heavy ion outflows in response to energy inputs from the global simulation. Test the impact of these outflows on the present magnetosphere.
- Complete a study of the high tilt magnetosphere with revised photothermal and induced outflows.
- Extend these results to reveal diurnal dynamics of a high tilt magnetosphere.

Year 2

- Replace the MFMD dipole field with a multipole expansion, set by geodynamo simulation, beginning with the present magnetosphere.
- Simulate the magnetosphere using reference events, for representative phases of geomagnetic reversals, from the present field to the dipole moment minimum of a reversal.
- Perform test particle studies of nonadiabatic behavior and particle acceleration for each phase.
- Identify baseline behavior and response to solar wind variability for each phase.

Year 3

- Adapt the resultant code to Mercury by scaling back the extended ionosphere; and compare behavior with Mariner 10 observations, remote observations, and other simulation efforts.
- Adapt the resultant codes to Mars and compare behavior with observations and other efforts.
- Adapt kinetic inner magnetosphere code for each phase, and compute energetic particles for each phase.
- Adapt the resultant codes to Venus and compare behavior with Pioneer-Venus and other efforts.

Closure and Relevance

The proposed work will:

- Incorporate ubiquitous photothermal and induced ionospheric outflows, with dependence on local conditions, into a global simulation, and determine the impact of the ionospheric plasma.
- Predict behaviors of the ionospheric-dominated magnetosphere during geomagnetic field reversals, particular auroral and storm plasma formation at various stages of reversal.
- Explore the heliospheric interaction with other terrestrial planets, Mercury, Mars and Venus, including evaluations of production of escaping fast neutral atoms.

The proposed work falls within the areas known as “magnetospheric physics” and "comparative magnetospheres", and supports NASA missions with objectives in these areas. The NAS Decadal Research Strategy in Solar and Space Physics recognizes this area thusly (p.11): "The comparative study of planetary ionospheres and magnetospheres is a central theme of solar and space physics research." The SEC 2002 Roadmap (p.29) states that SEC missions traditionally fall into one or more of the four broad disciplines: solar, heliospheric, magnetospheric (including comparative magnetospheres), and ionospheric-thermospheric-mesospheric (ITM)."

While it is clearly impossible to plan now for a NASA mission to the terrestrial magnetosphere at the time of minimum field intensity, all magnetospheric missions are inherently planned for a field reversal period, insofar as the decline of the dipole moment is known to have accelerated markedly during the past 10-30 years. The following missions in the SEC Roadmap are specifically targeted toward comparative magnetospheric study of other solar system bodies that are in states resembling the terrestrial magnetosphere during a field reversal episode: Bepi-Colombo (Mercury), Mars Aeronomy Probe, Solar Connections Observatory for Planetary Environments (SCOPE), and Venus Aeronomy Probe.

Moreover, the SEC Roadmap (p.64-65) addresses the means for the study of comparative magnetospheres, stating: "while (Discovery) missions focus upon planetary themes, NASA and the planetary community should remain open to including Discovery missions that address comparative planetary environments."...."Historically, the major advances in both heliospheric physics and comparative magnetospheres resulted from collaboration between the Sun-Earth Connection and Solar System Exploration." The Decadal Research Strategy makes a specific recommendation that "The scientific objectives of the NASA Discovery Program should be expanded to include those frontier space plasma physics research topics that could not otherwise be accommodated by other spacecraft opportunities."

The recommended missions cannot be conducted effectively without the proposed Geospace community effort to anticipate and predict the environments that will be encountered at other planets. Such efforts must be based upon knowledge gained in the terrestrial space environment as embodied in our best simulation models of this system. The proposed effort to compare simulations with planetary observations will lead to high confidence in the credibility of our predictions for those planets as well as the field reversal magnetosphere of our own planet.

This work extends the SEC study of geospace response (to the solar and geomagnetic variability) to the longer time scales of “space climate”. Beyond the solar cycle and its minima lie the geomagnetic field reversals, with time scales of a few 100 yrs to a few 100 kyr, with minima resembling those of the solar cycle extending to 100 Myr and possibly longer. By addressing geological time scales and events with possible biological impacts [e.g., Reid et al., 1975], this study will enhance linkages between the Sun Earth Connections, Planetary Origins, and Structure and Evolution of the Universe themes. The proposed work supports existing efforts to model and simulate global geospace circulation by extending them to conditions beyond the range for which typical codes have been developed and tested. It will make use of existing and future observations of terrestrial planets to validate the predictions made, provide robust improvements in the generality of space environment simulations, and extend the state of the art in magnetospheric simulation.

Management and Cost

This modeling effort will make use of established cooperative agreements between the Goddard Space Flight Center and the Universities Space Research Association in Greenbelt MD. This agreement allows incremental funding of research efforts, and the onsite housing of research associates within Goddard Space Flight Center. It is anticipated that a part of the support requested in this proposal will be applied to the salary of USRA research associates who may support this and other tasks.

Responsibilities of Key Personnel

Dr. T. E. Moore, principal investigator, will guide the overall science effort goals and implementation of the investigation, assuring that priority is placed upon the best tradeoff between attainability and scientific importance. He will participate directly in planning and executing the simulation work including development of suitable model inputs from observations, validation of the results obtained, the comparison of the results with appropriate data sets, and the presentation and publication of the results.

Dr. M.-C. Fok, coinvestigator, is a research scientist with the GSFC Interplanetary Physics Branch, and is the principal architect of the kinetic energetic particle simulation model used in this work. She is also responsible for the modification of the test particle code to use global simulation fields rather than empirical model fields. She will participate in the proposed work on a day-to-day basis.

Dr. N. Tsygananko, coinvestigator, is a research scientist with USRA, Greenbelt MD. He will assist in the definition of the internal magnetic field for the simulation model, based on the Glatzmaier geodynamo simulation.

Dr. D. C. Delcourt, collaborator, is the architect of the 3D particle simulation code. He will participate in the definition of scientific goals and in the development of appropriate physical model and code features, and in the execution and interpretation of model run results, via network communications and teleconferencing, as well as periodic meeting attendance and visits.

Dr. G Glatzmaier, collaborator, is professor at the University of Southern California and director of the Center for the Origin, Dynamics and Evolution of Planets at USC. He will supply us with multipole expansions of the geodynamo fields produced in his simulations for selected states or phases of the reversal process, as necessary.

Dr. J. L. Horwitz, collaborator, will consult on the physical modeling of the topside ionosphere in response to magnetospheric energy inputs. His modeling efforts will cross-validate and provide a physical understanding of our empirically-derived relationships between energy fluxes into the ionosphere and the ion outflows that result.

Dr. R. M. Winglee, collaborator, is the principal architect of the multifluid magnetodynamic simulation code. He will support and review adaptations of his code, for use in specifying self-consistent fields within which test particle motions will be computed, as well as for specifying flux inputs into critical regions of the magnetosphere.

Dr. M. Hesse, collaborator, is the director of the GSFC Community Coordinated Modeling Center. He will support independent validation runs using CCMC public codes, specifically the BatsRUS global MHD simulation, as validation and for comparison with the results from the multifluid magnetodynamic simulation.

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Appendix 2: CURRICULUM VITAE

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Dr. Delcourt received the M.S. in Physics from Universite de Paris XI, Orsay, France, in 1981, and the Ph.D in Astronomy and Space Technics from University Paul Sabatier, Toulouse, France, in 1985. Dr. Delcourt was awarded a National Research Council Research Associateship in 1986, for research on the interpretation of Dynamics Explorer data on the basis of three dimensional particle trajectory calculations. He spent two years with the Space Science Laboratory, Marshall Space Flight Center, working with the Retarding Ion Mass Spectrometer (RIMS) science team in data analysis and interpretation. This work has led to the first quantitative global description of ionospheric plasma transport within the magnetosphere [Delcourt et al., 1989]. He was a research fellow of the Space Science Department of ESA/ESTEC from 1988 to 1991, and has extended his modeling efforts to include dynamic phenomena in the magnetosphere, particularly with regard to the particle acceleration effects of transient electric fields induced by the substorm dynamics of the magnetotail. Dr. Delcourt was awarded his Habilitation (to supervise student research) by the University Paul Sabatier (Toulouse III), Toulouse, France, in December, 1989. In 1991 he joined the research staff of the Universities Space Research Association, Huntsville, AL, working at the Marshall Space Flight Center on magnetospheric plasma transport. In 1992, he joined the research staff of CRPE (now CETP) which is a CNRS laboratory dedicated to the study of Earth and planetary environments. He is continuing his study of magnetospheric plasma transport and energization using a combination of in-situ measurements and numerical simulations.

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Dr. Mei-Ching Fok received the B. S. degree in Physics from the Chinese University of Hong Kong (CUHK) in 1980. She spent the year after in the Physics Department at CUHK as a teaching assistant. From 1981-1985, she taught Physics and Mathematics in a high school in Hong Kong. In the summer of 1985, she came to the United States with her husband to pursue graduate studies. In 1987, Dr. Fok received the M. S. degree in Physics from the Eastern Michigan University. In the following year, she was admitted to the Ph. D. program in the Department of Atmospheric, Oceanic & Space Sciences at the University of Michigan and received her Ph. D. degree in August 1993. Three months later, she was awarded an NAS/NRC Resident Research Associateship at NASA/Marshall Space Flight Center. In 1995 after she left the NRC program, she joined the Universities Space Research Association (USRA) at MSFC. In August 1997, Dr. Fok was transferred within USRA to the Goddard Space Flight Center to follow her NASA sponsor, Dr. Thomas E. Moore. She became a NASA employee in May 2001.

During her doctoral study, she performed statistical studies on the subauroral electron temperature enhancement, using measurements from AE-C and DE 2 satellites. Dr. Fok also developed a kinetic model to study the dynamics of the storm time ring current ions and the associated effects on the plasmasphere-ionosphere system. Her model is the first ring current model that incorporates a time-dependent plasmasphere model and thus resolves the instantaneous coupling between the energetic and thermal plasmas. At the Marshall Space Flight Center, Dr. Fok extended her ring current model into 3 dimensions and included realistic magnetic field configurations. Her model has been used to simulate the energetic neutral atom (ENA) emissions in the inner magnetosphere in support the IMAGE mission. She continues her work at GSFC on global modeling through wide collaborations with the modeling group at the Rice University, the MHD group at the University of Michigan, and scientists at CETP, France.

Selected Publications:

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Gary A Glatzmaier, Professor of Earth Sciences
University of California, Santa Cruz

Dr. Gary A Glatzmaier received a Bachelor of Science degree, magna cum laude, from Marquette University in 1971 and then served four years as an officer in the U.S. Navy teaching nuclear reactor physics. In 1980 he he received a Ph.D. in Physics from the University of Colorado. After two post doctoral positions, he spent 16 years at the Los Alamos National Laboratory developing three-dimensional time-dependent computer models to study the internal structure and dynamics of planets and stars. In 1998 he became a Professor of Earth Sciences at the University of California, Santa Cruz. In his studies of the Earth he developed separate models that simulate the global circulation and convection in the Earth's atmosphere, mantle and core. He produced the first successful computer simulations of the geodynamo, the mechanism in the Earth's fluid outer core that maintains the geomagnetic field. He has been an associate editor of the Geophysical and Astrophysical Fluid Dynamics journal since 1990 and has served on scientific committees for the AGU, SEDI, NRC, NSF, NASA, and DOE. He is a Fellow of the Los Alamos National Laboratory and of the American
Geophysical Union and in 1996 won IEEE Sydney Fernbach Award for his geodynamo simulations. He is currently the Director of the Center for the Origin, Dynamics and Evolution of Planets within the Institute of Geophysics and Planetary Physics at UC Santa Cruz.

Selected Publications:

Glatzmaier, G.A. (2002) Geodynamo simulations - How realistic are they? Ann. Rev. Earth Planet. Sci., 30, 237-257.

Roberts, P.H. and Glatzmaier, G.A. (2000) Geodynamo theory and simulations, Rev. Mod. Phys. 72, 1081-1123.

Glatzmaier, G.A., Coe, R.S., Hongre, L. and Roberts, P.H. (1999) The role of the Earth's mantle in controlling the frequency of geomagnetic reversals, Nature 401, 885-890.

Glatzmaier, G.A. and Roberts, P.H. (1997) Simulating the geodynamo, Contemp. Physics, 38, 269-288.

Glatzmaier, G.A. and Roberts, P.H. (1996) Rotation and magnetism of Earth's inner core, Science, 274, 1887-1891.

Glatzmaier, G.A. and Roberts, P.H. (1995) A three-dimensional self-consistent computer simulation of a geomagnetic field reversal, Nature, 377, 203-209.

Glatzmaier, G.A., Schubert, G. and Bercovici, D. (1990) Chaotic, subduction-like downflows in a spherical model of convection in the Earth's mantle, Nature 347, 274-277.

Hart, J.E., Glatzmaier, G.A. and Toomre, J. (1986) Space-laboratory and numerical simulations of thermal convection in a rotating hemispherical shell with radial gravity, J. Fluid Mech. 173, 519-544.

Glatzmaier, G.A. (1984) Numerical simulations of stellar convective dynamos. I. The model and method, J. Comp. Phys., 55, 461-484.

Thomas E. Moore, Branch Head
Interplanetary Physics Branch, NASA Goddard Space Flight Center, Greenbelt, MD USA 20771

Thomas E. Moore earned the B.S. in Physics in 1970, and the M.A. in 1971, from the University of New Hampshire. He received the Ph.D. in Astrogeophysics from the University of Colorado, Boulder in 1978. Returning to the University of New Hampshire, he worked on the dynamics of the plasma environment at geosynchronous orbit, pioneering the use of multiple spacecraft to resolve the space-time structure of magnetospheric substorm injections. He also was active in the observation of plasma and energetic particles above auroral displays from sounding rocket platforms, and developed the first model of solar EUV and acceleration effects on the composition of ionospheric outflows.

Dr. Moore joined NASA at Marshall Space Flight Center in 1983 as a member of the science team for the Retarding Ion Mass Spectrometer on the Dynamics Explorer Satellite. He has worked actively on the acceleration and outflow of ionospheric plasma, the resulting source of plasma for the magnetosphere, and the acceleration of ionospheric plasma by magnetospheric circulation and substorm phenomena. He supplied instrumentation for the TOpside Probe of the Auroral Zone (TOPAZ) series of sounding rocket payloads, the ARCS series of active experiment payloads, and the SCIFER and CAPER cusp payloads. At MSFC, he became the principal investigator for the Thermal Ion Dynamics Experiment and Plasma Source Instrument for the ISTP POLAR spacecraft, and originated the concept of the geopause, within which the Earth is the dominant supplier of matter.

Dr. Moore joined the Goddard Space Flight Center in May 1997, to serve as project scientist for the IMAGE mission, lead coinvestigator for the Low Energy Neutral Atom imager on IMAGE, and to pursue broader interests in the heliospheric plasma dynamics and heating. He pursues an active interest in numerical modeling of space plasmas, and in data acquisition, manipulation and visualization technologies. He has served as secretary and program committee member of the American Geophysical Union, Space Physics and Aeronomy section, and as a member of the Solar Probe science definition team, and the NASA Sun-Earth Connection Roadmap Committee. He currently serves as project study scientist for the Magnetotail Constellation Mission of the Solar Terrestrial Probes Program, and as a co-chair of the NSF Geospace Environment Modeling working group on M-I coupling via ionospheric plasma outflows.

Selected Publications:

Moore, T. E., M.-C. Fok, and M. O. Chandler, The dayside reconnection X line, J. Geophys. Res., 107(A10), 10.1029/2002JA009381, p.SMP 26, 2002.
Moore, T. E., et al., Low Energy Neutral Atoms in the Magnetosphere, Geophys. Res. Lett. 28, p.1143, 15 March 2001.
Moore, T. E., et al., The Low Energy Neutral Atom Imager for the IMAGE Mission, Space Sci. Revs, 91(1-2), p.155, 2000.
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Moore, T. E., C. J. Pollock, and D. T. Young, Kinetic core plasma diagnostics, in Geophysical Monograph #102, p.105, Am. Geophys. Un., Washington, DC, 1998.
Moore, T. E. et al., High-altitude observations of the polar wind, Science, 277, p.349, 1997.
Moore, T. E., et al., Plasma heating and flow in an auroral arc, J. Geophys. Res. 101, p.579, 1996.
Moore, T.E., and D.C. Delcourt, The Geopause, Revs. Geophys., 33(2), p. 175, 1995.
Moore, T.E., et al., The Thermal Ion Dynamics Experiment and Plasma Source Instrument, Space Sci. Revs, 71, p.409, 1995.
Moore, T. E., Origins of Magnetospheric Plasma, Rev. Geophys., Supplement, p.1039, 1991.

Nikolai Tsyganenko, Senior Research Scientist
Universities Space Research Association,

Professional preparation:

M.S. (1970) and Ph.D. (1974) in Geophysics, from the Dept. of Physics, University of St.-Petersburg, Russia.

Positions:

Aug. 2001 - present	Universities Space Research Association	Senior Research Scientist
Feb. 1994 - Aug. 2001	Raytheon ITSS (formerly Hughes STX)	Chief Scientist
Feb. 1992 - Feb. 1994	NASA Goddard SFC / NAS	Senior NRC Associate
Mar. 1973 - Feb. 1992	State University of St.-Petersburg, Institute of Physics	Junior (1973-77) and Senior (1977-92) Staff Scientist

Research/expertise area: Space physics/magnetospheric modeling; authored 75 papers and a monograph.

Selected recent publications:

Tsyganenko, N.A., Quantitative models of the magnetospheric magnetic field: Methods and results, Space Sci. Rev., **54**, 75-186, 1990.

Tsyganenko, N. A., D. P. Stern, and Z. Kaymaz, Birkeland currents in the plasma sheet, J. Geophys. Res., **98**, 19,455-19,464, 1993.

Tsyganenko, N. A., and M. Peredo, Analytical models of the magnetic field of disk-shaped current sheets, J. Geophys. Res., **99**, 199-206, 1994.

Tsyganenko, N. A., Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause, J.Geophys.Res., **100**, 5599-5612, 1995.

Tsyganenko, N. A., and D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems, J.Geophys.Res., **101**, 27,187-27,198, 1996.

Tsyganenko, N. A., Modeling of twisted/warped magnetospheric configurations using the general deformation method, J. Geophys. Res., **102**, 23,551-23,564, 1998.

Tsyganenko, N. A., S. B. P. Karlsson, S. Kokubun, T. Yamamoto, A. J. Lazarus, K. W. Ogilvie, C. T. Russell, and J. A. Slavin, Global configuration of the magnetotail current sheet as derived from GEOTAIL, WIND, IMP-8, and ISEE-1/2 data, J. Geophys.Res., **102**, 6827-6841, 1998.

Tsyganenko, N. A., and C. T. Russell, Magnetic signatures of the distant polar cusps: Observations by POLAR and quantitative modeling, J. Geophys.Res., **104**, 24,939-24,955, 1999.

Tsyganenko, N. A., Modeling the inner magnetosphere: The asymmetric ring current and Region 2 Birkeland currents revisited, J. Geophys.Res., **105**, 27,739-27,754, 2000.

Tsyganenko, N. A., A model of the near magnetosphere with a dawn-dusk asymmetry 1.Mathematical structure, and 2. Parameterization and fitting to observations, J. Geophys. Res., v.107 (A8), doi: 10.1029/2001JA000219 and 10.1029/2001JA000220, 2002a,b.

Tsyganenko, N. A., and T. Mukai, Tail plasma sheet models derived from Geotail particle data, J. Geophys. Res., v.108 (A3), 1136, doi: 10.1029/2002JA009707, 2003.

Tsyganenko, N. A., H. J. Singer, and J. C. Kasper, Storm-time distortion of the inner magnetosphere: How severe can it get ? J. Geophys. Res., v.108 (A5), 1209, doi: 10.1029/2002JA009808, 2003.

Appendix 3: CURRENT AND PENDING SUPPORT

Mei-Ching Fok

Agency/Contact	Brief Title	Period:Funding:	Commit
NASA R&A/J. Sharber	Plasma Transport & Energization	FY02: 0k$	20%
NASA IMAGE/J. Spann	Low Energy Neutral Atom Imager MO&DA	FY02: 10k$ -FY04	20%
NASA IMAGE/J. Spann	IMAGE Theory and Modeling	FY02: 27k$ -FY04	30%
MSFC NSSTC/G. Khazanov	UPOS: Radiation Belt Environment	FY02: 100k$ - FY03	30%
NASA R&A/J. Peterson	Modeling of ENA Imagery	FY03: 80k$ -FY05	30%
Pending Support:			
NASA EP/M. Mellott	SMEX/COMPASS	FY04: tbdk$ - FY08	20%

Thomas E. Moore

Agency/Contact	Brief Title	Period:Funding	Commit
NASA GGS/W. Peterson	POLAR/TIDE-PSI MO&DA	FY03: 420k$ -FY04	20%
NASA R&A/W. Peterson	Plasma Transport & Energization	FY03: 42k$	20%
NASA IMAGE/W. Peterson	Low Energy Neutral Atom Imager MO&DA	FY02: 482k$ -FY04	20%
NASA IMAGE/W. Peterson	IMAGE Mission Scientist	FY02: 0k$ -FY03	20%
NASA STP/W. Peterson	Magnetospheric Constellation Study	FY02: 0k$ - FY12	20%
Pending Support:			
NASA EP/M. Mellott	Magnetospheric Multiscale Mission	FY04: 26k$ - FY10	20%
NASA EP/M. Mellott	SMEX/COMPASS	FY04: 67k$ - FY09	20%
NASA EP/M. Mellott	SMEX/IBEX	FY04: 26k$ - FY09	20%

Nikolai Tsyganenko

Agency/Contact	Brief Title	Period:Funding:	Commit
NASA LWS / D. Sibeck	Global Modeling of Geomagnetic Field	FY03: $83K - FY05	40%
NSF / K. Baker	Storms in the Inner Magnetosphere	FY03: $65K -FY05	32%
NSF / K. Baker	Data-Based Open Magnetosphere	FY03: $36K - FY05	18%
Pending support:			
NASA SEC/GI/ W.Peterson	Plasma Sheet Based on Geotail Data	FY04 -FY06	10%

Appendix 4: BUDGET SUMMARY for RESEARCH PROPOSAL

Budget Details and Notes

Budget Notes

This proposal budget has been prepared using NASA GSFC guidance for full cost accounting practices. These practices are incorporated into a template budget form that has been used as the basis for all rates and overhead computations in this budget. The budget summary sheets break out direct civil service labor and "other" cost categories, which correspond roughly to the new costs associated with full cost accounting and the "old" costs normally reported for NASA SR&T proposals, respectively.

Appendix 5: FINAL PROGRESS REPORT

This report consists of two parts: the section entitled "Recent Progress" in the main section of the proposal to which this is attached (not repeated here), and the following section summarizing publication activity:

Publications attributed to current SR&T support:

Cladis, J. B, H. L. Collin, O. W. Lennartsson, T. E. Moore, W. K. Peterson, and C. T. Russell, Observations of centrifugal acceleration during compression of the magnetosphere, Geophys. Res. Lett., 27(7), p.915, 2000. This paper established that centrifugal flinging motions of field lines can effect substantial acceleration of heavy ions, especially when the motion is impulsive as in response to the shock leading a CME.

Cowley, S.W.H., and C. J. Owen, A simple illustrative model of open flux tube motion over the dayside magnetosphere, Planet. Space Sci., 37(11), p.1461, 1989.

Delcourt, D.C., T. E. Moore, B. L. Giles, and M.-C. Fok, Quantitative Modeling Of Modulated Ion Injections Observed By Polar-Tide In The Cusp Region, J. Geophys. Res., 25(A11), p.25191, 2000. This study shows that the entry of solar wind plasma is modulated by nonadiabatic effects owing to the sharp and variable curvature of open field lines connecting the heliosphere to the geosphere.

Delcourt, D. C. , T. E. Moore, S. Orsini and A. Millilo, J.-A. Sauvaud, Centrifugal Acceleration Of Ions Near Mercury, Geophys. Res. Lett., 29(12), p.32-1, 15 June, 2002. This is an initial exploration of nonadiabatic particle behavior in a much smaller magnetosphere, in which such behavior is made more pervasive by the small scales of the structures.

Delcourt, D. C., S. Grimald, F. Leblanc, J.-J. Berthelier, A. Millilo, A. Mura, S. Orsini, and T. E. Moore, A quantitative model of the planetary Na^+ contribution to Mercury's magnetosphere, Ann. Geophys., in press, 2003. This paper is discussed in the main body of this proposal.

Fok, M.-C., T. E. Moore and W. N. Spjeldvik, Rapid enhancement of radiation belt electron fluxes due to substorm dipolarization of the geomagnetic field, J. Geophy. Res. 106(A3), p.3873, 2001a. This is our first exploration into the involvement of substorm dipolarizations in the acceleration of relativistic radiation belt electrons.

Fok, M.-C., R. A. Wolf, R. W. Spiro, and T. E. Moore, Comprehensive computational model of the Earth's ring current, J. Geophys. Res., 106(A5), p.8417, 2001b. This effort demonstrated the extension of the Rice Convection Model to include pitch angle distributions and conservation of the higher magnetic moments. It has proven immediately useful in the understanding IMAGE ring current observations.

Fok, M.-C., T. E. Moore, and D. C. Delcourt, Modeling of inner plasma sheet and ring current during substorms, J. Geophys. Res., 104, 14,557-14,569, 1999. This is the paper, based on empirical field models, with which our more recent simulations of substorm dipolarization in MHD fields have been compared.

Fok, M-C, T E Moore, G R Wilson, J D Perez, X Zhang, P C:son Brandt, D G Mitchell, E C roelof, J-M Jahn, C J Pollock, and R A Wolf, Global ENA IMAGE simulations, Space Science Revs., in press, 2003.

Horwitz, J. L., and T. E. Moore, Core Plasmas in Space Weather Regions, IEEE Trans, vol. 28, 6, pp. 1840-1853, December 2000. This a review paper summarizing the role of low energy geogenic plasmas in space weather throughout the magnetosphere.

Moore, T E, M O Chandler, D C Delcourt, B L Giles, W K Peterson, C T Russell, J Wygant, Ionospheric Incorporation into the Plasma Sheet, EOS Trans. AGU, Spring Meeting Supplement, 2002. This is the initial report of our Fall 2001 equatorial data set, which will be the basis for our proposed study of ionospheric incorporation in the plasma sheet.

Moore, T. E., M.-C. Fok, and M. O. Chandler, The dayside reconnection X line, J. Geophys. Res., 107(A10), p.SMP 26, 2002. (DOI: 10.1029/2002JA009381). This paper unifies the antiparallel and component descriptions of reconnection, and is concerned mainly with macroscopic distribution issues. It shows that reconnection extends well away from the sites of antiparallel reconnection along X lines that traverse the global dayside magnetopause.

Moore, T.E., M.O. Chandler, M.-C. Fok, B.L. Giles, D.C. Delcourt, J.L. Horwitz, C.J. Pollock, Ring Currents and Internal Plasma Sources, Space Science Reviews, 95(1-2): 555-568, January 2001. This is a Space Science Reviews "challenge" paper arguing that strong ring currents such as we have in the terrestrial magnetosphere can only occur where there are substantial internal sources of plasma.

Moore, T. E., B. L. Giles, D. C. Delcourt, and M.-C. Fok, The plasma sheet source groove, J. Atmos. Solar Terr. Phys., 62(6), p.505, 2000. This is our study of polar wind trajectory reversibility showing that ionospheric outflows can never be identified as a source of the plasma sheet by backward trajectory tracing from the plasma sheet (and also that the plasma sheet should be intrinsically unstable owing to velocity space structuring.

Moore, T.E., R. Lundin, et al., Plasma source processes in the high latitude ionosphere, IN "Sources and Losses of Magnetospheric Plasmas", ed. by B. Hultqvist, G. Paschmann, and M. Øeroset, Kluwer, Dordrecht, 1999. This is our review chapter on ionospheric outflows, which has been widely cited, though insufficiently taken to heart by the global simulation community, to date.

Moore, T.E., et al., Heliosphere-Geosphere Interactions Using Low Energy Neutral Atoms, Space Science Reviews, Special Issue, in press, 2003. This paper makes use of modeling results from this study in support of the interpretation of low energy neutral atom images of the Earth.

Perez, J. D., M.-C. Fok, and T. E. Moore, Deconvolution of energetic neutral atom images of the Earth's magnetosphere, Space Sci. Revs., 91(1-2), p.421, 2000. This paper is part of the IMAGE mission handbook issue of SSR. Deconvolution methods were tested against our ring current simulations in anticipation of the real IMAGE data set.

Strangeway, R. J., C. T. Russell, C. W. Carlson, J. P. McFadden, R. E. Ergun, M. Temerin, D. M. Klumpar, W. K. Peterson, T. E. Moore, Cusp Field-Aligned Currents and Ion Outflows, J. Geophys. Res. 105(A9), p.21129, 2000. This paper initiated the study of local ionospheric outflow response to local magnetospheric and solar wind energy inputs.

Appendix 6: STATEMENTS OF COMMITMENT